Development of a high gradient permanent magnetic separator (HGPMS)

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\section*{Abstract}

An innovative high gradient permanent magnetic separator (referred here as ZCLA HGPMS) was developed for recovering weakly magnetic minerals. Effect of key operating variables on the separation performance of a full-scale ZCLA HGPMS for recovering ilmenite from Pan Steels Midi Concentration Plant was investigated. Results indicated that the rotation speed and slope of the separating cylinder played a major role in enhancing the concentrate grade and titanium recovery. A titanium recovery of 80.8\% with a concentrate grade of 19.6\% was obtained by ZCLA-U_500/C_2_400 HGPMS at 7.0 t/h feed volume. While the ZCLA-U_950/C_2_1800 HGPMS recovered of 77.5\% at a concentrate grade of 19.5\% at 30 t/h feed volume. These results outperformed the vertical ring high gradient magnetic separator installed in the plant due to achieving higher separation efficiency through containing and no separation matrix that can clog while utilizing less energy all reason why the ZCLA HGPMS was developed.

\section*{1. Introduction}

Magnetic separation techniques are the simplest method to separate magnetic from nonmagnetic materials. They have a variety of applications in different industries such as: mineral beneficiation, food, textiles, plastic and ceramic processing industries (Veranda et al., 2013). The first attempt to apply permanent magnets to the dressing of magnetite ores was back in the 17th century with fuller a patenting the separation of iron ore using a magnet in 1792 (Derkach and Datsuk, 1947).

Since the early 1990s, the development of rare earth permanent magnet materials has greatly rekindled the research and development of magnetic separation technology and equipment using permanent magnets. High gradient magnetic separation (uses an applied electric field to generate magnetism) as an effective method for recovering fine weakly magnetic particles separation has undergone dramatic developments, and has also achieved extensive application during this time (Svoboda and Jujita, 1987). However, conventional electromagnetic high gradient magnetic separators greatest challenges to overcome when applied to treat metallic minerals such as hematite are the after matrix clogging and high energy consumption (Zeng and Zeng, 2009). This is why the ZCLA HGPMS was developed to solve these issues of high energy consumption by utilizing the magnetic force generated from permanent magnets and possessing no matrix that could clog.

\section*{2. Experimental}

\subsection*{2.1. ZCLA HGPMS and its principle}

The ZCLA HGPMS consists of permanent magnet, separating cylinder, support platform and drive (Fig. 1). As shown in Fig. 2, the magnetic system is the core of the ZCLA HGPMS. It uses high performance rare-earth permanent magnet materials to generate the required magnetism for the separation based on the properties of magnet and the characteristics of particle size being beneficiated. The magnetic system is fixed outside the separating cylinder: The poles face is concave, producing a concave magnetic field. Between the two main poles and auxiliary poles, extrusion magnetic poles are formed, enhancing the magnetic field intensity of magnetic pole surfaces which we call the magnetic separator. Separating cylinder adopts the permeability stainless steel materials. The magnetism permeates through the stainless steel separating cylinder while the permanent magnetic medium is installed inside the cylinder, which improves the recovery rate of magnetic materials.

By adopting the earth permanent magnetic materials to making special combination, the magnetic system of ZCLA HGPMS formed an introverted type of magnetic circuit structure. Compared with the open counterpart, its magnetic pole face reserved for concave arc, and the distribution of magnetic field is similar to a semi closed magnetic system, which increases the depth and intensity of magnetic field (Fig. 3). The surface magnetic field of magnetic separation drum reaches 0.9 T.

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When the separator is in operation, feed materials are introduced into the separating cylinder from the feed trough. A non-homogeneous magnetic field is produced in the separating cylinder by the fixed magnetic system. Magnetic minerals are attracted close to the cylinder by the magnetic force, and are transported to the top of the separating cylinder as it rotates, and discharged with the assistance of flushing water to concentrate trough. The non-magnetic minerals pass through the cylinder and discharge out the non-magnetic discard launder.

The main parameters of the separator are listed in Table 1.

2.2. Property of ore samples

The ilmenite concentrate from the vanadic titanomagnetite ore of Panzhihua in Sichuan province, China, is the primary source for titanium dioxide in China. It accounts for more than 90% of the titanium resource in China and over 35% globally (Wu et al., 2011), and regarded as a strategically important titanium reserve. This titanium ore has a relatively high Fe and TiO₂ grade. A complicated flowsheet combining gravity, magnetic separation, flotation and leaching processes are be used to extract the TiO₂ and Fe values from the ore (Belardi et al., 1998; Li et al. 2006, Li and Yang 2011). From November 7 to December 26, 2011, on-site tests using the ZCLA-Φ500 × 400 HGPMS were carried out in Pan Steels Midi Concentration Plant.

The feed assay is shown in Table 2 with the mineralogical composition presented in Table 3. The target mineral, TiO₂ is contained in ilmenite, titanomagnetite and silicates and has a feed concentration of 9.11%. The main gangue mineral in the ore is silica (SiO₂) with a content of 34.43%.

2.3. Test conditions

The optimum process parameters for the ZCLA-Φ500 × 400 HGPMS were investigated though changing the rotating speed of cylinder, slope of cylinder, feed rate, and tailings rinse water test. With the optimal parameters used for the production run. Due to the limitation of plant operating conditions, the feed concentration was kept at 25% solids due to limitation of the plant operating system. During the test, a sample was taken every hour while four...
samples were taken for the analytical sample. The results of these four analytical samples were averaged to give that result for a given parameter.

2.4. Evaluation method

The concentrate grade, titanium recovery and separation efficiency were used for evaluating the separation performance. Titanium recovery and separation efficiency were calculated as:

\[ e = \frac{\beta(\alpha - \theta)}{\alpha(\beta - \theta)} \]

\[ E = e \left(1 - \frac{\beta(\beta - \theta)}{\beta(\beta - \alpha)}\right) \]

where \( \alpha \) is the feed grade, \( \beta \) is the concentrate grade, \( e \) is the titanium recovery of concentrate, \( \beta_M \) is the maximum titanium grade of ilmenite mineral (50% TiO\(_2\)), \( E \) is the separation efficiency.

3. Results and discussion

3.1. Effect of rotation speed of cylinder

The effect of rotation speed of cylinder in the separating zone of the ZCLA-\(\Phi\)500 × 400 HGPMS was first studied, with the separator at a feed solid content of 25%, treatment capacity of 6.25 t/h, and magnetic medium of 3 mm spacing, respectively. As shown in Fig. 4, the rotation speed has a very significant effect on the titanium recovery of concentrate product and separation efficiency. Both recovery and separation efficiency increased with increasing rotation speed. A maximum recovery and separation efficiency gained at the rotation speed of 17 r/min. Further increasing the rotation speed resulted in reduced recovery and separation efficiency. On the other hand, the concentrate grade was found virtually independent of the rotation speed of the cylinder. The rotation speed of cylinder determines the retention time of the ores in the separating cylinder, thus posing a significant impact on the separation performance of the separator. As can be seen from Fig. 4, a rotation speed of 15 r/min was suitable for the tested minerals. A too slow rotation speed of cylinder, nevertheless, would inevitably decrease the solids throughput of the separator.

3.2. Effect of slope of cylinder

The separation results of the ZCLA-\(\Phi\)500 × 400 HGPMS applied to the material as a function of the slope of the cylinder is shown in Fig. 5. It can be seen that slope of the cylinder was an important...
variable in determining the titanium recovery and the separation efficiency of magnetic product. The recovery started to decrease when the slope of the cylinder was higher than 12°. Based on the results in Fig. 5, the optimal slope of the cylinder was set at 12° for all proceeding tests.

Adjusting the slope of the cylinder would cause a change in flow velocity of the slurry. The greater the slope of the cylinder, the faster the slurry flow velocity in the cylinder. As shown in Fig. 5, the ilmenite recovery decreased as the slope of the cylinder increased. This decrease in the recovery was due to the fact the flow velocity of the slurry in the cylinder is too fast to recover the ultrafine or partially liberated ilmenite minerals so were washed out when they are subjected to stronger hydrodynamic forces against relatively weaker magnetic capturing forces. At a cylinder slope of 12°, a concentrate grade of 17.02% and a titanium recovery of 86.02% were obtained for the Panzhihua ilmenite.

3.3. Effect of feed rate

As shown in Fig. 6, the titanium recovery decreased as the feed rate increased. At a slow feed rate, the ZCLA HGPMS could capture almost all magnetic mineral particles, resulting in a high recovery. As the feed rate increased there was more magnetic particles to recover and due to the units fixed magnetic intensity only the first layer of the magnetic minerals could be captured as concentrate product. Along with hydrodynamic and mechanical forces the recovery and separation efficiency reduced with increasing feed rate. Surprisingly that the concentrate grade did not change with additional increase in feed rate. Based on the results in Fig. 6, it is apparent that a feed rate of 7.0 t/h was ideal to be used in subsequent tests, using the ZCLA-Φ500 x 400 HGPMS separators.

3.4. Effect of tailings rinse water

In ZCLA HGPMS separators tailings rinse water was installed to improve the quality of magnetic products by losing the magnetic media matrix and by washing away non-magnetic solids trapped in the captured magnetic particles. Therefore, adding tailings rinse water can generally give higher concentrate grades. There was no flow meter installed in ZCLA-Φ500 x 400 HGPMS, we could only compare the results with (or opened)/without (or closed) tailings rinse water. According to the separating results in Table 4, when feed concentration (25%), magnetic medium of spacing (3 mm), slope of cylinder (12°) and rotation speed of cylinder (15 r/min.) were kept optimum adding tailing rinse water by turning on tailings rinse water increased concentrate grade (from 17.02% to 20.15%), but decreased recovery (from 86.02% to 79.23%). However, the overall separation efficiency still increased (from 41.61% to 47.99%).

### Table 4
Comparison tests with/without tailings rinse water,

<table>
<thead>
<tr>
<th>Tailings rinse water</th>
<th>TiO₂ Grade (%)</th>
<th>Weight (%)</th>
<th>Titanium recovery (%)</th>
<th>Separation efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed Concentrate Tailings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed</td>
<td>10.52 17.02 3.14</td>
<td>53.17</td>
<td>86.02</td>
<td>41.61</td>
</tr>
<tr>
<td>Opened</td>
<td>10.51 20.15 3.72</td>
<td>41.33</td>
<td>79.23</td>
<td>47.99</td>
</tr>
</tbody>
</table>

Operating conditions: (1) feed concentration = 25.00%, (2) magnetic medium of spacing = 3 mm, (3) slope cylinder = 12°, (4) rotation speed of cylinder = 15 r/min, (5) treatment capacity = 7.0 t/h.

### Table 5
Performance of ZCLA-Φ500 x 400 HGPMS under optimum conditions (including operation data without using the HGPMS).

<table>
<thead>
<tr>
<th>Separator</th>
<th>TiO₂ grade (%)</th>
<th>Weight (%)</th>
<th>Titanium recovery (%)</th>
<th>Separation efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZCLA-Φ500 x 400 HGPMS</td>
<td>10.81 19.56 3.8</td>
<td>44.48</td>
<td>80.48</td>
<td>45.93</td>
</tr>
</tbody>
</table>

Operating conditions: (1) feed concentration = 25.00%, (2) magnetic medium of spacing = 3 mm, (3) slope cylinder = 12°, (4) rotation speed of cylinder = 15 r/min, (5) treatment capacity = 7.0 t/h, (6) opened tailings rinse water.
47.99%). Therefore, the intensity of tailings rinse water has to be controlled to ensure the removal of non-magnetic particles with minimal effect on the magnetic solids.

3.5. Comparison of separation performance

Table 5 shows the results of ZCLA-Φ500 × 400 HGPMS for that was operated continuously for 30 days in Pan Steels Midi Concentration Plant with under optimal operating conditions. The results showed the ZCLA-Φ500 × 400 HGPMS achieved excellent results, with 80.48% recovery at a concentrate grade of 19.56% TiO₂.

Due to the excellent performance of the ZCLA-Φ500 × 400 HGPMS, in 2010–2011, a ZCLA-Φ950 × 1800 HGPMS was installed in magnetic separation process of Pan Steels Midi Concentration Plant. The results were compared with those of the vertical ring high gradient magnetic separator (Slon-2000 HGMS and Slon-1500 HGMS). (as shown in Figs. 7 and 8). The optimum separation results are illustrated in Table 6. It is clear that similar or even slightly better separation performance could be obtained by a single stage separation using the ZCLA-Φ950 × 400 HGPMS, as compared with the two-stage separation using the Slon-2000/1500 HGMS. The test results demonstrated that the ZCLA HGPMS is effective in processing Panzhihua ilmenite ores.

4. Conclusions

The ZCLA HGPMS method, which combines a magnetic system formed outside the separating cylinder with the ore slurry feeding into the separating cylinder, presents an innovative HGMS technology.

The rotation speed and slope of separating cylinder are operating controlling variables that affect the concentrate grade and titanium recovery. For Panzhihua ilmenite ores, there was an optimum of rotation speed and slope of separating cylinder in which the maximum separation efficiency was achieved.

The ZCLA HGMPS is a new generation of continuous HGMS with a higher beneficiation ratio, without matrix clogging. The equipment is suitable for processing ilmenite, hematite, limonite and other weakly magnetic minerals.
Acknowledgements

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References


